

Article

Multi-Run Genetic Algorithm Approach for Optimal Design of Concentric Reluctance Magnetic Gears

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Abstract

This paper presents a systematic optimization methodology for reluctance magnetic gears (RMGs) using genetic algorithms to maximize peak torque within fixed volume constraints. A multi-run parametric study with population sizes ranging from 50 to 150 individuals demonstrates robust convergence toward remarkably similar geometric proportions, with a best torque of 430.15 Nm and minimal variation (0.65%) across different configurations. The optimization redistributes radial dimensions, achieving a 95% torque improvement over uniform distribution by significantly increasing inner rotor teeth thickness by 85% while reducing modulator thickness by 74%. The most significant outcome is the emergence of a consistent design trend across all independent runs, providing general guidelines on how the RMG internal geometry should be arranged to maximize peak torque.

Keywords: reluctance magnetic gear; genetic algorithm; optimization; magnetic torque; modeling

1. Introduction

In recent years, magnetic gearboxes (MGs) have attracted growing attention as a superior alternative to conventional mechanical gear systems due to their contactless power transmission principle [1]. These devices are widely employed in cutting-edge sectors such as electric vehicles (EVs), sustainable power generation, and aerospace applications, where they offer distinctive advantages including the absence of lubrication requirements, reduced maintenance, low noise and vibration levels, and intrinsic overload protection [2–7]. Particularly, the adoption of magnetic gearboxes in wind power generation facilities is becoming increasingly attractive due to the growing demand for electricity [8] and the need for reliable, low-maintenance devices, especially for offshore wind turbines or those installed in remote locations where mechanical gearbox failures constitute one of the primary causes of system downtime [9,10].

The operating principle of MGs and the governing equations are extensively discussed in [1,11–14].

Despite all the advantages, traditional MG systems, such as coaxial surface-mounted permanent magnet gears (SPMGs), face significant challenges. The extensive use of rare-earth permanent magnets (e.g., NdFeB) makes them extremely expensive and subject to market price fluctuations [15,16]. Furthermore, operation at high mechanical speeds induces



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substantial eddy current losses in the high-speed rotor magnets, drastically reducing efficiency. Additionally, centrifugal forces at elevated speeds compromise the structural robustness of the device, potentially causing magnet detachment and catastrophic failure [17,18].

To overcome these limitations, a different technology has been proposed: Reluctance Magnetic Gears (RMGs). The fundamental difference between the two devices lies in the rotor configuration, as Figure 1 shows. While conventional MGs mount permanent magnets on both the high-speed rotor and low-speed rotor, RMGs employ a high-speed rotor composed solely of an iron core with salient poles, completely eliminating permanent magnets from this component [19,20]. This distinctive feature makes RMGs inherently more economical and robust, reducing eddy current losses in the high-speed rotor and facilitating operation in harsh environments or at ultra-high speeds. The reduction in permanent magnet material can reach approximately 20–40% compared to SPMG systems [21], significantly lowering manufacturing costs and reducing dependency on rare-earth elements.

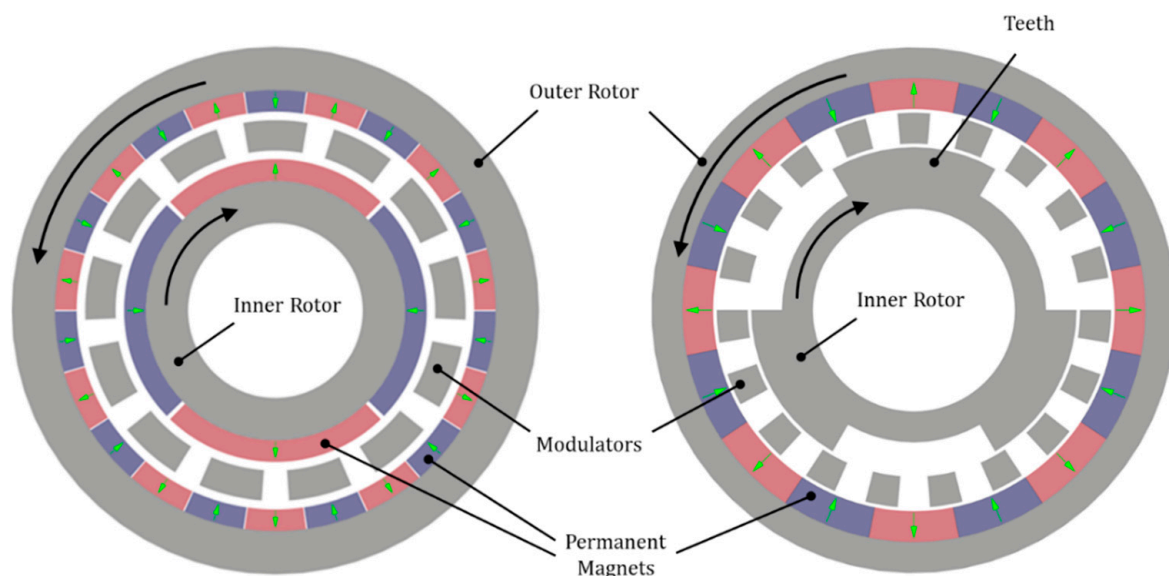


Figure 1. Comparison between SPMG (left) and RMG (right) configurations.

The primary applications for RMGs include industrial high-speed motors and ultra-high-speed drive systems, aerospace actuators and propulsion systems where mechanical robustness and reliability are critical, and renewable energy systems such as wind and hydrokinetic systems [17,22]. However, this design choice inevitably results in lower torque density compared to permanent-magnet gear systems. To achieve the same torque level as a conventional MG, an RMG may require an active volume up to five times larger [15] or significantly thicker magnets, increasing both the ferromagnetic material usage and overall device dimensions. This fundamental trade-off between cost and robustness on one hand and torque density on the other represents the central challenge in RMG design.

The research on MGs and RMGs shares common methodological foundations, with both systems extensively analysed through two-dimensional finite element simulations and optimized using intelligent algorithms such as NSGA-II [19,23]. Three-dimensional simulations are considered essential to account for edge effects, which can reduce the estimated torque by ten to forty percent [15,18,23]. To address this limitation, hybrid frameworks coupling two-dimensional GA-based optimizers with three-dimensional parametric models have been proposed, demonstrating consistent parameter trends between the two approaches while significantly improving accuracy over purely 2-D designs [24]. Alternatively, magnetic equivalent circuit models based on reluctance networks have been

combined with multi-objective genetic algorithms, achieving satisfactory accuracy compared to finite element analysis at a fraction of the computational time [25].

However, the optimization objectives differ significantly depending on the specific technology and application. For conventional MGs, the goal is to maximize an already high torque density through magnetic material optimization such as Halbach configurations [26,27]. Genetic algorithms have been applied to optimize coaxial MGs with different permanent magnet arrangements (surface mounted, consequent-pole, and spoke-type), revealing a non-trivial relationship between gear ratio and output torque where performance degrades beyond a critical gear ratio value due to manufacturing limitations [28]. Multi-objective formulations have also been employed to simultaneously maximize transmitted torque per unit mass while minimizing the moment of inertia of the moving parts, addressing practical constraints for automotive powertrain applications [29]. Furthermore, loss computation methodologies have been developed for coaxial MGs, highlighting the major loss sources in ferromagnetic components and evaluating corrective measures including permanent magnet segmentation [30].

For RMGs, optimization is vital to compensate for an inherently lower torque capability. Wide torque fluctuations represent a critical challenge, and research has focused on flux-barrier rotors, asymmetric or chamfered salient pole configurations, and non-ferromagnetic composite materials for the rotor core [17–20]. Further investigations have examined magnet arrangement schemes and the application of genetic algorithms to balance torque capability with low ripple [31].

Despite these advances, a systematic approach to optimize the complete radial geometry of concentric RMGs under fixed volume constraints remains underexplored. Most existing studies focus on individual component optimization or single-aspect performance improvement rather than holistic dimensional optimization considering the interdependencies between all radial layers, including outer rotor yoke and teeth, modulator poles, inner rotor teeth and yoke, and air gaps.

This work addresses the challenge of maximizing peak torque in RMGs within a constrained external volume. The optimization problem is formulated using five normalized weight variables that govern the radial thickness distribution of all active components (outer yoke, permanent magnets, modulators, inner rotor teeth, and inner rotor yoke), while the outer radius (r_0) and inner shaft radius (r_7) are held as fixed constraints. A genetic algorithm coupled with 2-D finite element simulations is employed to solve the optimization problem. The main contributions of this work are: (i) the formulation of the RMG radial optimization through normalized weight variables that inherently satisfy the fixed-volume constraint, eliminating the need for nonlinear geometric constraints; (ii) the holistic optimization of all radial dimensions simultaneously, capturing the interdependencies between layers that component-level optimization cannot address; and (iii) a multi-run approach with varying population sizes and independent random initializations, specifically designed to identify design trends rather than isolated optimal solutions, providing general design principles for RMG radial geometry.

2. Principle of Operation of Reluctance Magnetic Gear

The operating principle of the coaxial RMG is based on modulation of the magnetic flux paths. In this system, the magnetic field produced by the permanent magnets (PM) on the stator is modulated by the ferromagnetic pole pieces of the intermediate rotor (the modulators) and by the salient poles of the inner rotor. This modulation generates flux harmonics with different spatial frequencies (pole pair numbers) and angular velocities; when these harmonics couple appropriately across the air gap, torque is transmitted according to the principle of minimum reluctance [15,19,20,32].

Coaxial RMGs consist of three concentric components [15,17,19] (Figure 1):

1. Outer ring: It carries n_1 permanent magnets mounted on its surface. These are typically NdFeB magnets and provide the magnetomotive force without requiring external excitation.
2. Modulator ring: Located between the outer and inner rings, it is formed by n_2 ferro-magnetic segments (pole pieces) whose role is to modulate the magnetic field. These segments are usually made from laminated electrical steel to reduce iron losses (hysteresis and eddy currents).
3. Inner ring: A salient-pole structure with n_3 teeth. The absence of PMs on this rotor is motivated by mechanical robustness: at high speeds, surface-mounted magnets could detach due to centrifugal forces. Moreover, omitting magnets on the high-speed rotor eliminates eddy-current losses in magnets themselves, improving overall efficiency at high rotational speeds.

For the case considered here, the modulator ring is assumed fixed while the other two rings act as rotors. For this configuration, the magnitude of the gear ratio (GR) of the RMG can be expressed as

$$GR = \frac{2p_1}{n_3} = \frac{n_1}{n_3} \quad (1)$$

p_1 can be expressed as a function of the gear ratio and the number of teeth of the inner rotor as

$$\begin{cases} p_1 = 0.5(GR_{int} n_3 + 1) & \text{if } GR_{int} \cdot n_3 \text{ is odd} \\ p_1 = 0.5(GR_{int} n_3 + 2) & \text{if } GR_{int} \cdot n_3 \text{ is even} \end{cases} \quad (2)$$

where GR_{int} denotes the integer part of the desired transmission ratio. From (2), it is apparent that GR_{int} influences the number of pole pairs on the outer rotor. These formulas are used because integer transmission ratios have been observed to increase torque ripple, degrading motion smoothness and increasing acoustic noise. Equation (2) therefore prescribes an appropriate number of magnets on the outer rotor so as to avoid excessive ripple.

Accordingly, during early design stages, a target value for the gear ratio is chosen, but it must be chosen such that the resulting number of pole pairs p_1 is an integer [15,18].

The number of modulator segments must also be appropriate and is calculated using a specific relationship:

$$n_2 = n_1 + n_3 \quad (3)$$

In summary, these specific expressions allow for obtaining a gearbox whose transmission ratio is close to the design target while providing smoother torque (thanks to the effectively non-integer-like interaction) and mechanical stability (thanks to pole symmetry and proper pole integrity).

3. RMG Optimization Formulation

3.1. FEM Model

The objective of this work is to optimize the dimensions of the active parts to achieve the maximum possible torque within a defined volume. This volume is bounded by the inner shaft radius r_7 and the outer rotor external radius r_0 , which were established as fixed constraints in this preliminary design phase and are reported in Table 1. This table summarizes the principal specifications of the reference RMG model considered in this study, materials included. Regarding all the ferrous parts, M270-35A has been considered, and its B-H curve is shown in Figure 2. Regarding the outer PM, NdFeB magnets have been taken into account, with magnet permeability $\mu_x = \mu_y = 1.05$ H/m, coercivity $H_C = 955,000$ A/m and electrical conductivity $\sigma = 0.667$ MS/m. The PMs have been modeled with rectangular cross-section geometry. A Dirichlet boundary condition

($A = 0$) was imposed on a circular boundary of radius 75 mm, which fully encloses the RMG geometry.

Table 1. RMG model parameters.

Description	Parameter	Symbol	Unit	Value
Geometrical Parameters kept fixed	Outer rotor external radius	r_0	mm	70
	Inner shaft radius	r_7	mm	27
	Available radial span	Δr	mm	41
	Air gap thickness	$dr_2 = dr_4$	mm	1
	Length	L	mm	1000
Materials	Outer yoke	M270-35A	-	-
	Outer PM	NdFeB	-	-
	Modulators	M270-35A	-	-
	Inner rotor	M270-35A	-	-
RMG configurations specifications	Target gear ratio	GR_T	-	5.5
	Effective gear ratio	GR	-	5.33
	Outer rotor pole pairs	p_1	-	8
	Outer rotor PM	n_1	-	16
	Modulators	n_2	-	19
	Inner rotor teeth	n_3	-	3

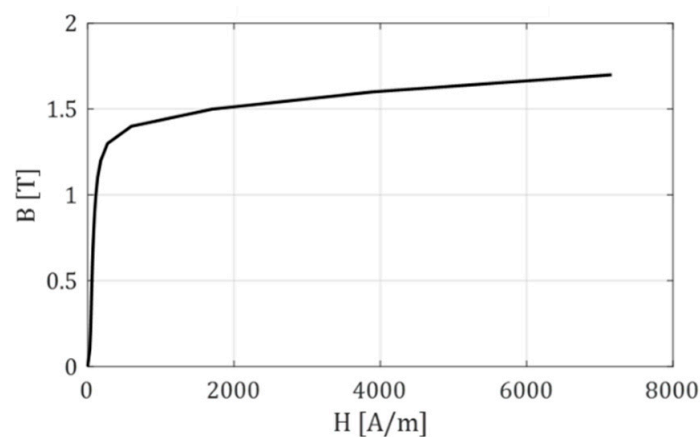


Figure 2. M270-35A B-H curve used for the simulations.

Once the target gear ratio GR_T and the number of inner rotor teeth n_3 are selected, the number of permanent magnets on the outer rotor (n_1) and the number of modulator segments (n_2) are uniquely determined by Equations (2) and (3), respectively. These relationships ensure proper magnetic field harmonic interaction between the rotors and modulator for effective torque transmission.

Mesh Convergence Analysis

A mesh sensitivity analysis was conducted to determine appropriate element sizes for the FEM simulations. The study evaluated the influence of mesh refinement on each RMG component independently, using the finest discretization (0.5 mm uniform) as reference. Figure 3 presents the percentage torque variation as a function of mesh element size for each component, with all other regions held at the reference mesh size.

The results demonstrate that the air gap mesh exerts the dominant influence on torque accuracy, with variations reaching 0.30% when the element size is increased from 0.5 mm to 1.0 mm. This is physically expected, as the Maxwell stress tensor integration used for torque computation is performed across the air gap, where steep flux density gradients

require adequate spatial resolution. The remaining components exhibit significantly lower sensitivity: modulators and permanent magnets show variations below 0.06% and 0.05% respectively, while the outer rotor yoke and inner rotor teeth remain virtually insensitive (below 0.005%) across the entire mesh size range.

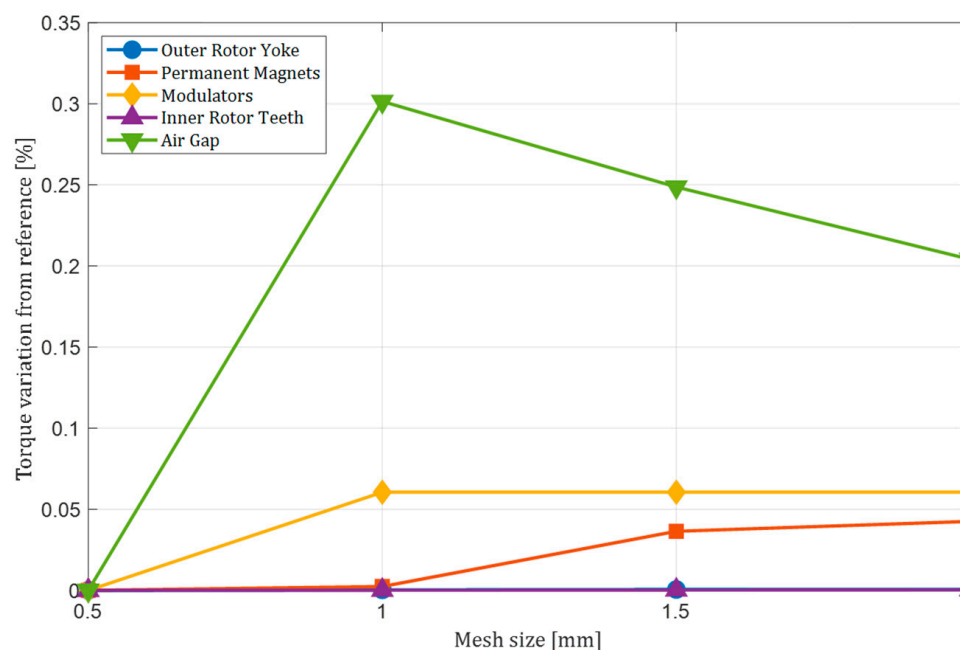


Figure 3. Percentage torque variation from the reference solution (0.5 mm uniform mesh) as a function of element size, with all other regions held at the reference discretization.

However, it should be noted that this sensitivity analysis was performed on the uniform-weight configuration. In general, the sensitivity of the solution to mesh discretization may vary depending on the specific geometric configuration. Components with reduced radial thickness would contain fewer elements for a given mesh size, potentially amplifying discretization errors that appear negligible in the uniform case. Similarly, regions experiencing higher magnetic saturation levels may require finer spatial resolution to accurately capture the nonlinear material behavior. Based on these considerations, a conservative mesh strategy has been adopted and is shown in Table 2: 0.5 mm for the air gaps, given their dominant influence on torque computation; 1.0 mm for permanent magnets, modulators, and inner rotor components; and 2.0 mm for the outer rotor yoke, whose negligible sensitivity allows coarser discretization without compromising accuracy.

Table 2. Mesh discretization parameters and resulting element distribution for the FEM model.

Region	Region Area [mm ²]	Mesh Size [mm]	Elements Number
Outer yoke	3258	2.0	9549
PMs	2560	1.0	10,463
Modulators	1249	1.0	9285
Inner rotor	2615	1.0	13,749
Air gap	3421	0.5	41,250

3.2. Problem Formulation

Since the object of study is a concentric RMG, these dimensions can be expressed in the form of radii. Considering Figure 4, the radii r_0 and r_7 were constrained, representing the maximum outer radius and minimum inner radius of the model, respectively. The

remaining radii visible in the figure are those to be optimized. The calculation model is similar to the one used in [33].

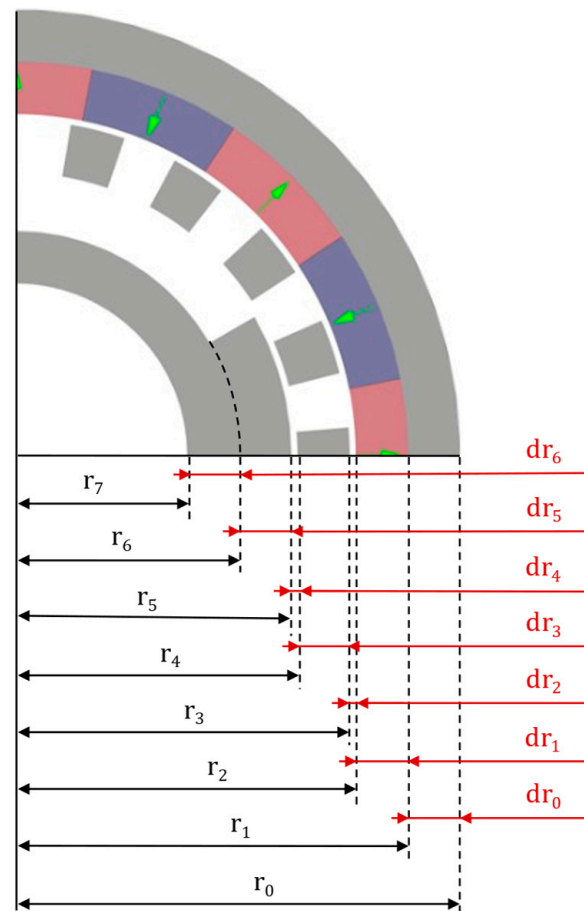


Figure 4. RMG radial geometry and design variables.

Given the global size constraint imposed, the radii are mutually dependent and calculated using the following formula:

$$r_i = r_{i-1} + \frac{dr_i}{\sum_{k=1}^n dr_k} \Delta r \quad (4)$$

where Δr is the allowable radial variation between r_0 and r_7 , and dr is the step between two adjacent radii, given by

$$dr_i = \frac{y_{P_i}}{\sum y_P} \Delta r \quad (5)$$

The term y_P effectively indicates a weight to be applied to dr , and it is precisely this term that is the subject of the optimization. Five normalized variables (y_{P1} , y_{P2} , y_{P3} , y_{P4} , y_{P5}) were defined as design variables, bounded between 1 and 10, representing the relative proportions of the radial thicknesses. In these conditions, the objective function is formally defined as

$$f(y_P) = \max \{ T(y_{P1}, y_{P2}, y_{P3}, y_{P4}, y_{P5}) \} \quad (6)$$

where $f(y_P)$ is the objective function and T is outer rotor torque.

4. Optimization Strategy

The optimization was performed using a genetic algorithm, specifically through the GA Toolbox in MATLAB R2024b.

The genetic algorithm flowchart is presented in Figure 5, while its configuration parameters are reported in Table 3. The process begins with a random generation of the initial population, initialized with independent random seeds to ensure different starting conditions across runs. The fitness function is calculated for each individual and it was defined as the negative outer rotor torque, evaluated through finite element method (FEM) simulations using FEMM 4.2 software, at the maximum torque angle (30° mechanical). The five normalized weight variables (y_{P1} through y_{P5}) were bounded between 1 and 10, defining the feasible design space. The GA was configured using MATLAB's default settings for all parameters except population size and maximum generations. Specifically, the selection strategy employs stochastic uniform sampling, where each individual is assigned, a probability of being selected as a parent proportional to its fitness value. At each generation, the best individuals (elite count $\approx 5\%$ of the population) are directly preserved in the next generation. The remaining individuals are generated through crossover and mutation: the scattered crossover operator, applied with a crossover fraction of 0.8, creates each child by randomly selecting genes from either parent, while the adaptive feasible mutation operator generates random perturbations that adapt their magnitude based on the recent success of the algorithm, respecting the bound constraints on the design variables. At the end of each generation, the algorithm checks whether one of the stopping criteria is satisfied. If so, the optimization terminates; otherwise, the operations are repeated starting from the selection of the elite individuals.

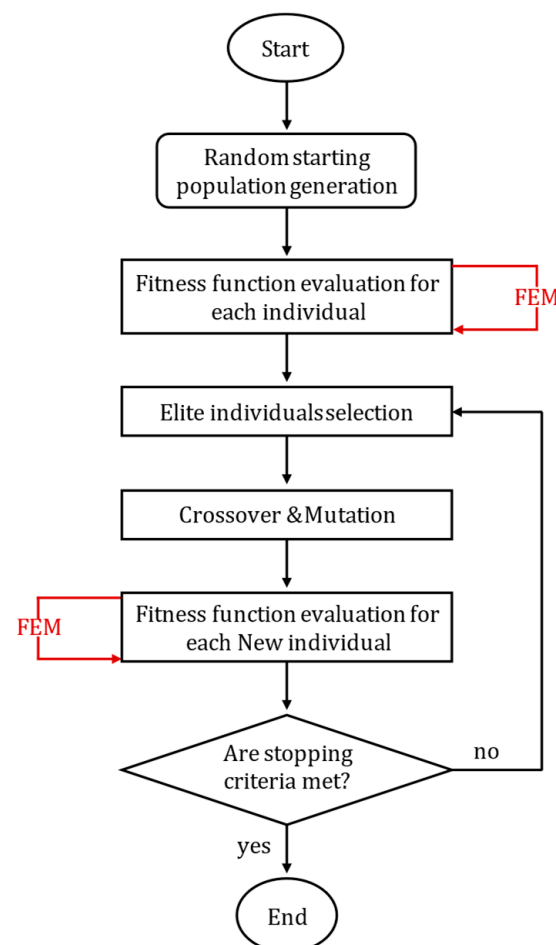


Figure 5. Genetic Algorithm flowchart.

Table 3. Genetic Algorithm Parameters.

Parameter	Value	Configuration
Population size	50, 75, 85, 100, 115, 125, 150	Variable across runs
Maximum Generations	300	Fixed for all runs
Elite Count	≈5% Pop (default)	Fixed for all runs
Crossover Fraction	0.8 (default)	Fixed for all runs
Function Tolerance	1×10^{-6} (default)	Fixed for all runs
Crossover Operator	Scattered	Fixed for all runs
Selection Strategy	Stochastic Uniform	Fixed for all runs
Mutation operator	Adaptive feasible	Fixed for all runs
Maximum Stall Generations	50 (default)	Fixed for all runs

A systematic parametric study was conducted by varying the population size across five different values (50, 75, 85, 100, 115, 125, and 150 individuals) while maintaining a constant maximum generation limit of 300 for all runs. All other GA parameters were kept at their MATLAB default values throughout the entire study. The primary purpose of this multi-run approach extends beyond assessing the sensitivity to population size: by repeating the optimization with different random initializations and population sizes, it is possible to evaluate whether the resulting geometric proportions represent a consistent design trend rather than an isolated solution dependent on specific GA settings. By testing multiple population sizes, we can: (i) assess the trade-off between solution quality and computational time; (ii) identify the minimum population size required for reliable convergence; (iii) evaluate whether larger populations yield significantly better results to justify the increased computational burden; and (iv) verify the consistency of the optimized radial proportions across independent runs.

Maintaining a constant generation limit across all runs ensures a fair comparison between different population sizes. This allows direct assessment of convergence behaviour and solution quality as a function of population size alone, without confounding effects from varying generation limits.

All remaining GA parameters were maintained at MATLAB's default values mainly because limiting the parametric study to population size and generation limit reduces the complexity of the analysis and the total number of required runs, making the study more manageable while still providing meaningful insights. In addition, using default values ensures reproducibility and allows for direct comparison with other studies in the literature that employ similar GA configurations.

5. Results and Discussion

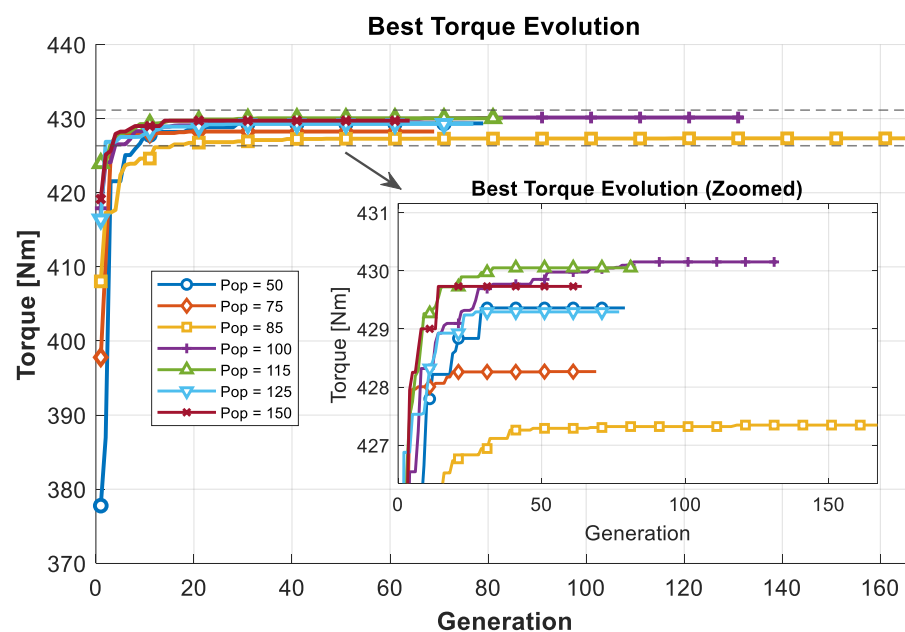
To assess the robustness and reliability of the genetic algorithm optimization, many independent runs were performed with varying population sizes while maintaining constant maximum generations and default MATLAB parameters for all other settings. Each run was initialized with a different random population, ensuring independent exploration of the design space.

5.1. Statistical Robustness Analysis

Table 4 and Figure 6 summarize the optimization results for different configurations. All runs successfully converged to the stopping criterion, indicating that the average change in fitness over 50 consecutive generations fell below the specified tolerance (1×10^{-6}). Notably, convergence was achieved well before the maximum generation limit in all cases, with the number of generations ranging from 64 (pop = 150) to 167 (pop = 85).

Table 4. Optimization results for different population sizes.

Population Size	Best Torque [Nm]	Generations to Convergence	Function Evaluation
50	429.36	79	3766
75	428.27	69	4978
85	427.35	167	13,450
100	430.15	132	12,645
115	430.05	83	9168
125	429.29	77	9218
150	429.70	64	9238

**Figure 6.** Best torque evolution across generations for optimization runs with different population sizes. The inset provides a zoomed view of the convergence region.

Despite different random initializations and population sizes, all configurations converged to remarkably similar optimal torque values, as illustrated in Figure 6. Statistical analysis of the realized runs reveals exceptional consistency, since the difference between the best torque overall and the worst torque overall is 2.81 Nm, representing a percentage variation of 0.65%. The fact that the realized runs converged to within less than 1% of each other shows high confidence in the reliability of the optimization methodology. In addition, the standard deviation of maximum peak torque values is 0.24% relative to the mean value equal to 429.17 Nm.

The insensitivity to population size is particularly noteworthy. Even the smallest tested configuration (50 individuals) achieved a final torque of 429.36 Nm, only 0.18% below the best result. This indicates that for this particular design space, adequate genetic diversity for effective optimization can be achieved with relatively modest population sizes.

Interestingly, the intermediate population size of 100 individuals achieved the highest torque (430.15 Nm). This non-monotonic behaviour (where neither the smallest nor largest population performed best) reflects the stochastic nature of genetic algorithms and suggests that population sizes in the range of 75–150 are equally effective for this problem.

5.2. Optimal Geometry Configuration

The optimal radial dimensions are presented in Table 5, expressed both as absolute thicknesses (d_r) and as percentages of the available radial space. The corresponding normalized weight variables (y_p) that define these proportions are shown in Table 6.

Table 5. Optimal geometric dimension.

Parameter	Symbol	Value [mm]	Percentage of Δr
Outer rotor yoke thickness	dr_0	3.582	8.74%
Outer rotor PM thickness	dr_1	9.573	23.34%
Outer Air Gap	dr_2	1.000	2.44% (fixed)
Modulators thickness	dr_3	2.140	5.22%
Inner Air Gap	dr_4	1.000	2.44% (fixed)
Inner rotor teeth thickness	dr_5	15.188	37.04%
Inner rotor yoke thickness	dr_6	10.517	25.65%

Table 6. Weight values of optimal configuration.

Weight	Value	Interpretation
y_{p1}	1.9640	Outer yoke weight
y_{p2}	5.2492	Outer PM weight
y_{p3}	1.1736	Modulators weight
y_{p4}	8.3282	Inner teeth weight
y_{p5}	5.7671	Inner yoke weight

The optimization results reveal several key insights into reluctance magnetic gear design. From Table 5, it is evident that the majority of the available radial span is occupied by the inner rotor components (inner rotor teeth plus inner rotor yoke), representing a combined 62.69% of the total space. This substantial allocation to the inner rotor can be attributed to two complementary physical mechanisms. First, given that the inner radius is fixed and that, in general, this type of magnetic gear produces higher torque at larger radii [34], shifting the magnetic active components toward larger radii inherently increases torque capacity. Second, the substantial teeth thickness maximizes the magnetic reluctance variation during rotation, which directly enhances reluctance torque production through increased permeance modulation.

The outer rotor permanent magnet thickness ranks as the second-largest allocation at 23.34%. Combined with the outer rotor yoke (8.74%), the outer rotor occupies 32.08% of the radial span, nearly half the allocation given to the inner rotor. The substantial PM thickness is justified by the critical need for strong magnetic field excitation, particularly considering that the entire magnetic field is generated exclusively by these outer stator magnets, with no magnets present on the high-speed rotor. Regarding the outer yoke thickness, its relatively modest dimension evidently does not contribute significantly to torque enhancement, but its specific electromagnetic role will be examined in detail in the following section through flux density analysis.

The final optimized thickness is dr_3 , corresponding to the modulator poles. This parameter yields perhaps the most surprising result, representing only 5.22% of the total span, the smallest allocation aside from the fixed air gaps. This minimal percentage suggests that a thin modulator structure is sufficient to provide adequate magnetic field modulation without wasteful occupation of radial space that could be more productively allocated to the permanent magnets or the inner rotor salient poles. The thin modulator effectively performs its harmonic field-shaping function while maximizing space for the primary torque-producing components.

5.2.1. Geometric Comparison with Initial (Uniform) Configuration

To quantify the improvement achieved through optimization and validate the need for sophisticated optimization rather than intuitive uniform distribution, Table 7 compares the initial (uniform) and optimized configurations.

Table 7. Geometric comparison between uniform and optimized configurations.

Configuration	Radii [mm]	Value	dr [mm]	Value	y _P	Value
Initial	r ₀	70	dr ₀	8.2	y _{P1}	1
	r ₁	61.8	dr ₁	8.2	y _{P2}	1
	r ₂	53.6	dr ₂	1	-	-
	r ₃	52.6	dr ₃	8.2	y _{P3}	1
	r ₄	44.4	dr ₄	1	-	-
	r ₅	43.4	dr ₅	8.2	y _{P4}	1
	r ₆	35.2	dr ₆	8.2	y _{P5}	1
	r ₇	27	-	-	-	-
Optimized	r ₀	70	dr ₀	3.582	y _{P1}	1.9640
	r ₁	66.418	dr ₁	9.573	y _{P2}	5.2492
	r ₂	56.845	dr ₂	1	-	-
	r ₃	55.845	dr ₃	2.140	y _{P3}	1.1736
	r ₄	53.705	dr ₄	1	-	-
	r ₅	52.705	dr ₅	15.188	y _{P4}	8.3282
	r ₆	37.517	dr ₆	10.517	y _{P5}	5.7671
	r ₇	27	-	-	-	-

The initial design allocated equal weights to all variable components ($y_{P1} = y_{P2} = y_{P3} = y_{P4} = y_{P5} = 1$), resulting in uniform radial thicknesses of 8.2 mm for each layer. This “equal distribution” represents a natural starting point that an engineer might choose without detailed electromagnetic analysis; it maximizes geometric symmetry and simplifies manufacturing. In this case, the maximum torque is 220.54 Nm.

However, the optimization produced a redistribution of radial space. Indeed, the inner rotor yoke, inner teeth and outer PM increased by 28%, 85% and 17% respectively, while the modulators thickness and outer yoke decreased by 74% and 56% respectively.

These changes are not minor refinements; they represent fundamental rebalancing of the magnetic circuit. The 85% increase in inner rotor teeth thickness, in particular, demonstrates that the uniform distribution severely under-utilized the most critical torque-producing component.

The corresponding radii (r_0 through r_7) shift substantially, with the inner rotor expanding outward significantly.

5.2.2. Flux Density Distribution Comparison with Initial (Uniform) Configuration

Figures 7 and 8 present the magnetic flux density distribution for the initial uniform-thickness configuration and the run with $\text{pop} = 100$ resultant configurations, respectively. In the first case, the flux distribution appears relatively uniform across most components, with no severe saturation detected in any region. However, the inner rotor and its teeth exhibit extensive areas of very low flux density (cyan/light blue regions, <0.5 T), suggesting significant under-utilization of this critical component. Despite the uniform 8.2 mm thickness allocation, the inner rotor is not magnetically loaded to its full capacity. Higher values are exhibited at the tips of the teeth, and the maximum $|B|$ is 1.2 T.

The modulator poles show non-uniform flux distribution, particularly in the gaps created by the inner rotor teeth. The flux density in the modulators varies considerably, from 0.3 T in some regions to 1.99 T at the outer edges adjacent to the air gap. This gradient indicates uneven magnetic loading with localized saturation occurring in small regions of the modulators.

Regarding the outer permanent magnets and outer yoke, the magnet region displays relatively homogeneous flux density distribution (predominantly green-yellow, 1.0–1.15 T). The outer yoke exhibits a recurring circumferential pattern, with flux density alternating

between lighter green zones (0.3 T) and darker orange zones (1.3 T). This pattern reflects the pole pitch modulation imposed by the permanent magnets. Importantly, the field lines have adequate space to spread, avoiding saturation in the yoke structure.

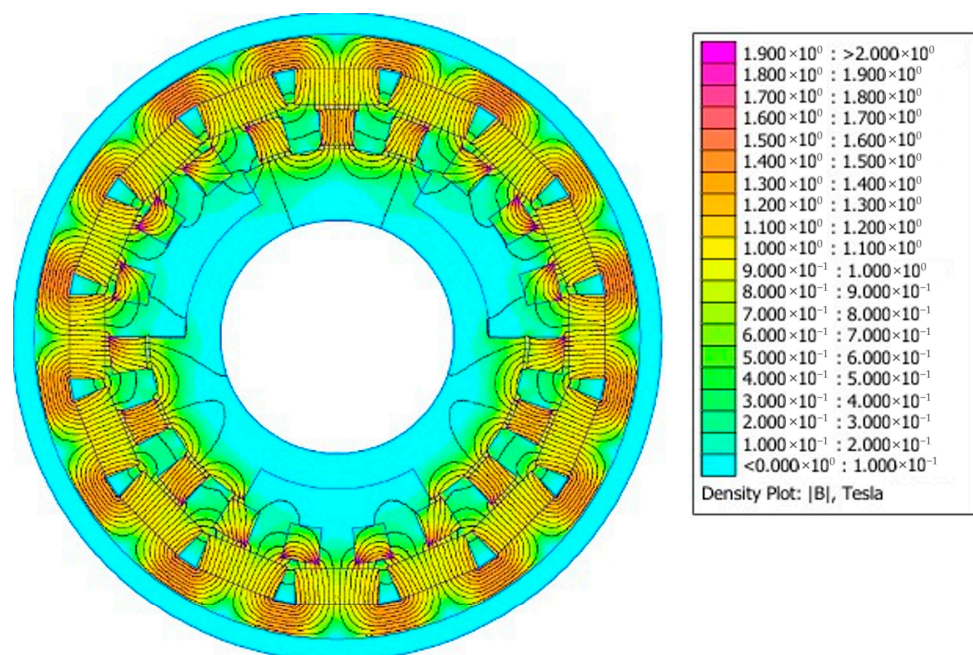


Figure 7. Magnetic flux density distribution for the uniform-weight configuration.

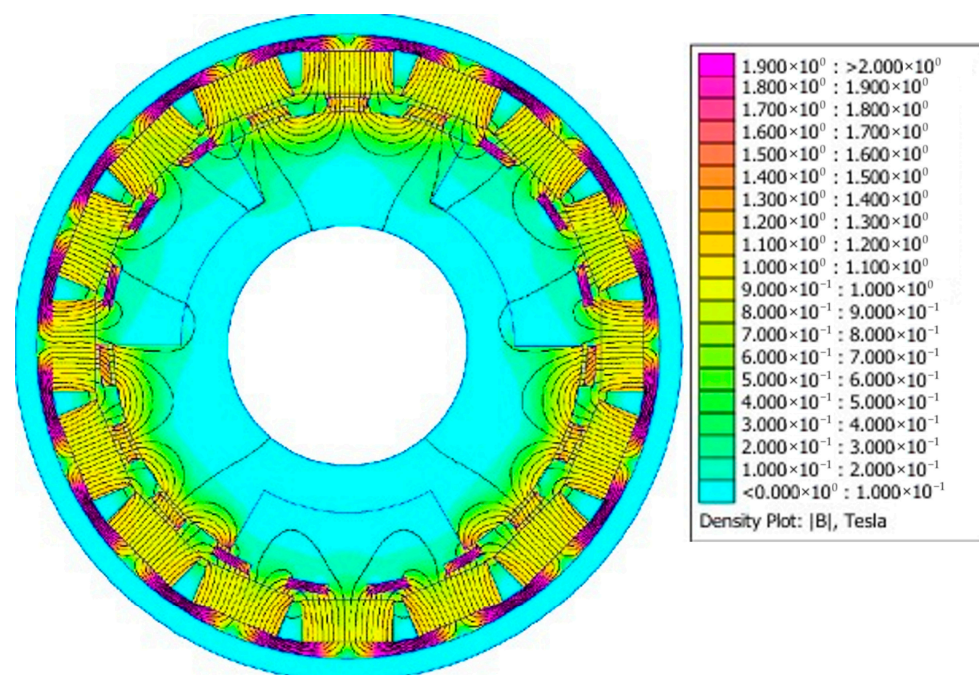


Figure 8. Magnetic flux density distribution for the optimized configuration.

Following the genetic algorithm optimization, the radial dimensions changed substantially, resulting in a dramatically different magnetic flux density distribution, as shown in Figure 8.

Similar to the initial uniform configuration, the optimized inner rotor still exhibits large regions with low flux density, indicating persistent under-utilization in certain circumferential positions. As in the previous case, the flux density peaks at the teeth tips, reaching

a value of 1.44 T in the most loaded position. However, a critical difference emerges: due to the significantly larger inner radius in the optimized geometry, the total area experiencing useful flux density is substantially greater. Although local under-utilization persists in inter-pole regions, the increased overall volume of magnetically active material at larger radius compensates, contributing to higher torque production.

The modulator poles present the most evident change. Because of the marked reduction in thickness, localized saturation now appears in the modulator segments adjacent to the inner rotor tooth gaps, with flux densities exceeding 1.9 T (magenta regions) and indicating a dramatic magnetic bottleneck. This saturation represents the trade-off inherent in the optimized design: the modulator is sized at the minimum thickness necessary for field modulation, accepting localized saturation in exchange for freeing radial space for the higher-priority inner rotor components.

The permanent magnets exhibit no significant differences from the initial configuration, since flux density remains homogeneous, though the colour distribution suggests slightly lower average values. Indeed, as in the previous case, the flux density is around 0.76 T in the zones close to the airgap, while a value of 1.12 T is reached on the lateral edges of PMs.

The outer yoke, however, shows substantial changes. While the recurring circumferential pattern persists, the flux density has intensified, indicating severe saturation of the ferromagnetic material with associated core losses. This saturation in the outer yoke arises from the significantly reduced thickness.

Regarding iron losses, the optimized configuration is expected to produce higher core losses compared to the initial uniform design. This is supported by two observations: first, the peak flux density values are consistently higher in the optimized geometry across all ferromagnetic components (with the exception of the permanent magnets), and second, the saturated regions are more spatially extensive, particularly in the modulators and outer yoke. Since core losses exhibit a nonlinear dependence on flux density (hysteresis losses scaling approximately with B^n , with $n = 1.6 \div 2.2$ and eddy current losses with B^2 according to classical Steinmetz theory), even moderate increases in local flux density can produce disproportionate loss increases.

The aim of the present work is to demonstrate a systematic optimization methodology and to identify general design trends for RMG radial geometry as a function of initial population size and generational evolution. The optimization was formulated as a single-objective problem targeting exclusively peak torque maximization, without incorporating iron losses or efficiency as constraints or secondary objectives. The quantitative evaluation of core losses and the development of a multi-objective optimization framework balancing torque performance against efficiency are identified as key directions for future research.

5.2.3. Torque Comparison with Initial (Uniform) Configuration

Figure 9 presents, as a function of the inner rotor angle, the torque comparison between the uniform-thickness RMG configuration and the optimized configuration resulting from the run with population size of 100. The torque waveforms are shown for both the inner and outer rotors in both configurations. The dashed lines indicate the mean torque values for the inner rotor cases.

A significant increase in mean torque can be observed in the optimized configuration compared to the uniform one: the outer rotor torque increases from 219.4 Nm to 427.0 Nm, while the inner rotor torque rises from 41.5 Nm to 81.6 Nm, corresponding to a 95% improvement in both cases. This result confirms that the redistribution of radial thicknesses produces a proportional improvement on both rotors.

Considering the mean outer rotor torque of the optimized configuration and the total active volume enclosed between r_0 and r_7 , the resulting torque density is 35.6 kNm/m^3 , which is comparable in order of magnitude to values reported in [15,17,18], although these studies address different topologies and optimization objectives.

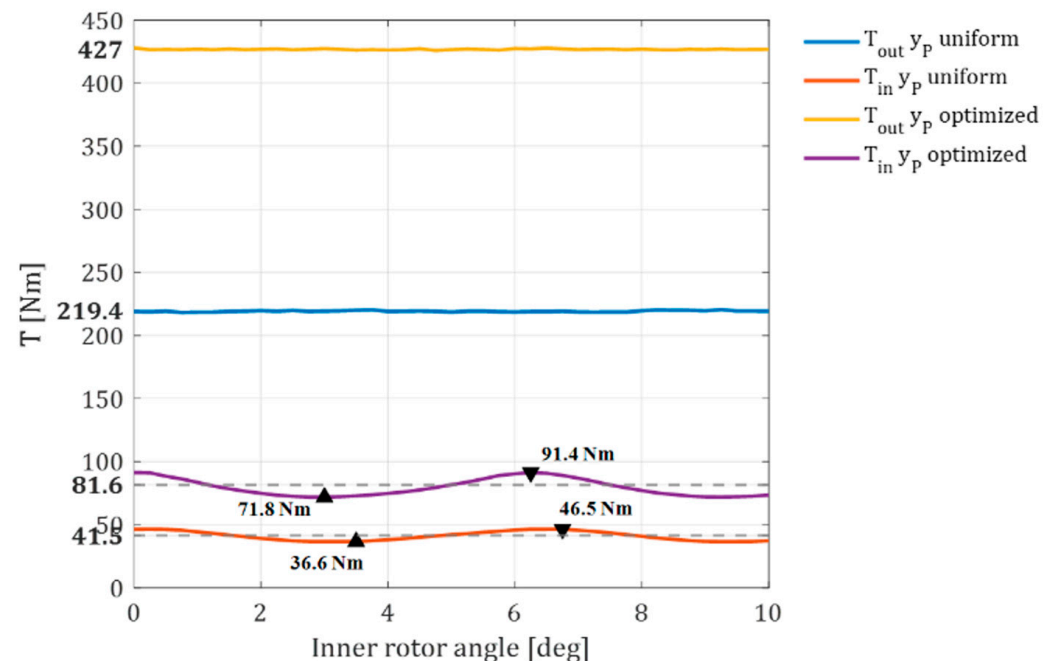


Figure 9. Torque waveforms for uniform and optimized configurations as a function of inner rotor angle variation.

Regarding the torque ripple R , this was evaluated using the following expression:

$$R = \frac{\max(T) - \min(T)}{\text{mean}(T)} \cdot 100 \quad (7)$$

where T represents the generic torque and R expresses the ripple in percentage form. The analysis was performed on the inner rotor waveforms, which exhibit the most pronounced oscillations. For the uniform configuration, the torque ripple is 23.85%, while for the optimized configuration it amounts to 24.02%, with a difference of only 0.17 percentage points between the two cases. It should be noted that the relatively high torque ripple values observed in both configurations are partially attributable to the rectangular magnet geometry adopted in this study, which inherently produces a less sinusoidal air gap flux distribution compared to arc-shaped magnets. This result suggests that the variation in radial thicknesses predominantly affects the mean torque value, while its effect on the inner rotor torque ripple is virtually negligible.

Finally, compliance with the transmission ratio between the outer and inner rotors can be verified. In general, the outer rotor torque should equal GR times the inner rotor torque. For the uniform configuration, multiplying the mean inner rotor torque by the gear ratio yields $41.5 \times 5.33 = 221.2 \text{ Nm}$ compared to a simulated value of 219.4 Nm , resulting in a deviation of 0.81%. For the optimized configuration, the expected value is $81.6 \times 5.33 = 434.9 \text{ Nm}$, while the simulation returns 427.0 Nm , corresponding to a deviation of 1.86%. The larger deviation in the optimized case can be attributed to the more pronounced magnetic saturation in the modulators and outer yoke, which introduces nonlinear effects in the magnetic circuit and partially alters the harmonic coupling between the rotors. Nevertheless, both deviations remain limited, confirming the validity of the model and the substantial compliance with the expected gear ratio in both configurations.

5.3. Optimal Proportion Across Different Runs

Figure 10 presents the percentage distribution of radial thicknesses (dr_0 through dr_6) for the optimization runs with different population sizes. Despite different random initializations and population sizes ranging from 50 to 150 individuals, the optimized configurations exhibit remarkable consistency in their geometric proportions, revealing underlying physical principles that govern optimal RMG design.

Across all runs, the modulator thickness (dr_3) consistently represents the smallest allocation, with values ranging narrowly from 5.22% to 5.58%. This remarkably tight clustering confirms that a relatively thin modulator represents an optimal design principle despite the localized saturation observed in Figure 8. The optimization evidently determined that the torque benefits gained by reallocating radial space from the modulator to the inner rotor outweigh the penalties associated with modulator saturation.

The outer rotor components, outer yoke (dr_0) and permanent magnets (dr_1) also demonstrate low variability, with ranges of only 1.56% and 2.92%, respectively. This consistency suggests that these parameters are well-constrained by electromagnetic requirements: the permanent magnets must provide sufficient field excitation (favouring thickness), while the outer yoke leaves more space for torque-critical components. The air gaps (dr_2 and dr_4) were held constant at 1.0 mm across all optimizations, providing a fixed geometric constraint. Most notably, the inner rotor teeth thickness (dr_5) consistently occupies the largest percentage allocation in every run, though with greater variability (ranging from 31.42% to 53.34%) compared to other parameters. Cross-referencing with Table 4, a clear correlation emerges: runs exhibiting thicker inner teeth generally achieve higher torque values, suggesting that this parameter exerts dominant influence on torque production. This aligns with reluctance torque theory, where torque magnitude depends critically on the variation in magnetic permeance, which is directly proportional to salient pole thickness.

The population-50 run (Figure 10a) exhibits the most pronounced disparity, allocating 53.34% to the inner teeth, the highest value across all runs. Interestingly, this aggressive allocation does not translate to proportionally higher torque (429.36 Nm, comparable to other runs). Examining the configuration reveals that the “extra” thickness allocated to the teeth is predominantly taken from the inner rotor yoke (dr_6), which occupies only 10.85% in this case. A similar pattern appears in Figure 10e (pop. 115) and Figure 10g (pop. 150), where inner teeth occupy 47.90% and 41.81% respectively, while the inner yoke is reduced to 14.84% for pop = 115 and to 21.11% for pop = 150.

A critical insight emerges when examining the combined inner rotor allocation ($dr_5 + dr_6$): this sum remains remarkably constant across all runs, varying only from 62.25% (pop. 125) to 64.19% (pop. 50). This consistency reveals a fundamental design principle: maximizing torque requires not only substantial tooth thickness (for high reluctance variation) but also adequate radial positioning of these teeth away from the shaft center to maximize the moment arm.

The electromagnetic analysis in Figure 8 corroborates this interpretation, showing that the inner rotor yoke carries minimal magnetic flux and does not significantly participate in creating a magnetic flux path. Despite this apparent “under-utilization,” the optimization consistently allocated 11–31% of radial space to the inner yoke. This seemingly paradoxical result can be explained by recognizing that the inner yoke serves a geometric rather than purely magnetic function: it positions the salient poles at larger radius, thereby increasing the effective moment arm for torque production. The yoke acts as a structural spacer that determines the fulcrum distance for torque application.

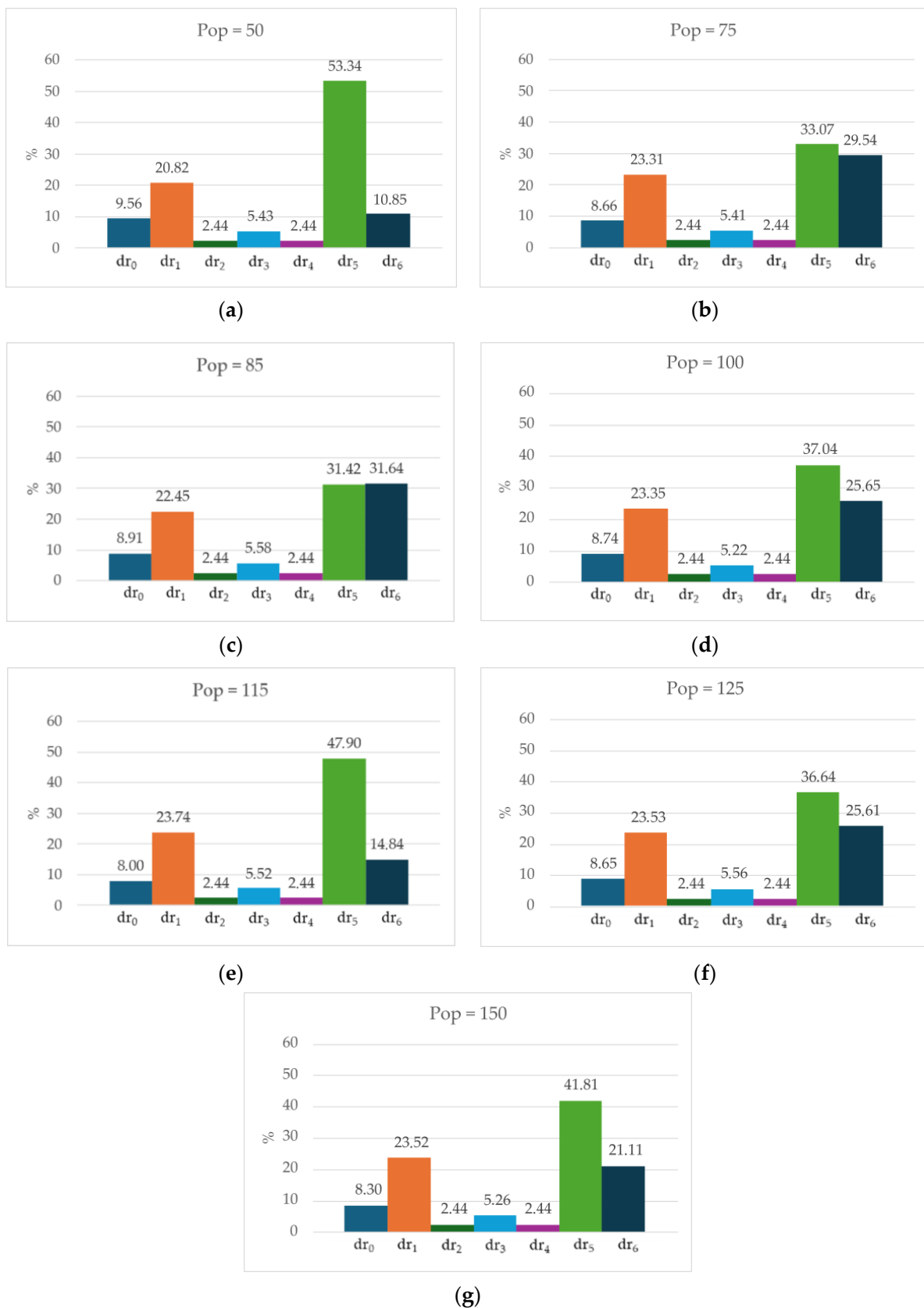


Figure 10. Percentage distribution of radial thicknesses for the optimization runs. (a) dr_i percentage distribution for Pop = 50; (b) dr_i percentage distribution for Pop = 75; (c) dr_i percentage distribution for Pop = 85; (d) dr_i percentage distribution for Pop = 100; (e) dr_i percentage distribution for Pop = 115; (f) dr_i percentage distribution for Pop = 125; (g) dr_i percentage distribution for Pop = 150.

In summary, the consistent geometric proportions across all runs, particularly the stable 62–64% combined inner rotor allocation, demonstrate that the genetic algorithm reliably converges to a fundamental RMG design principle: approximately two-thirds of available radial space should be dedicated to the inner rotor, with roughly equal priority given to tooth thickness (for reluctance variation) and yoke thickness (for radial positioning). The remaining one-third is divided between permanent magnets (~23%), modulators (~5%) and outer yoke (~9%).

6. Conclusions

This study demonstrated a genetic algorithm methodology for optimizing reluctance magnetic gear radial geometry, achieving 95% torque improvement (430.15 Nm vs. 220.54 Nm) over uniform distribution through strategic reallocation of radial space.

Multi-run validation with population sizes ranging from 50 to 150 individuals, each initialized with independent random seeds, revealed exceptional consistency (0.65% percentage variation), suggesting convergence toward a well-defined region of the design space. Notably, the most significant outcome of this multi-run approach is the emergence of a consistent design trend across all independent runs: regardless of population size and initial random individuals, the optimization converges toward similar geometric proportions. This general trend provides valuable physical insight into how the internal geometry of an RMG should be arranged to maximize peak torque. Specifically, the optimization consistently identified a fundamental design principle: allocate approximately 63% of radial space to the inner rotor (~37% teeth, ~26% yoke), with the remainder distributed among permanent magnets (~23%), modulator (~5%), and outer yoke (~9%).

Key insights include the following: (i) inner rotor teeth thickness is the dominant torque-producing parameter; (ii) the inner yoke serves a critical geometric function (radial positioning for moment arm maximization) despite minimal magnetic flux participation; (iii) strategic acceptance of localized saturation in modulator and outer yoke enables optimization of primary elements; and (iv) the torque ripple remains virtually unaffected by the radial redistribution, suggesting that thickness optimization primarily influences mean torque rather than torque quality.

The methodology provides practical design guidelines applicable to future RMG development and demonstrates that genetic algorithms reliably navigate complex electromagnetic design spaces. It should be acknowledged that the present work was formulated as a single-objective optimization targeting exclusively peak torque maximization. Future work should address iron losses torque ripples aspects within a multi-objective optimization framework, seeking Pareto-optimal configurations that balance torque performance against efficiency and torque quality.

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Abbreviations

The following abbreviations are used in this manuscript:

MG	Magnetic Gearbox
SPMG	Surface-mounted Permanent Magnet Gearbox
RMG	Reluctance Magnetic Gear
GA	Genetic Algorithm
PM	Permanent Magnet
FEM	Finite Element Method
Pop	Population

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